

# How the $X(5568)$ challenges our understanding of QCD

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## Abstract

We discuss the  $X(5568)$  particle recently announced by the D0 Collaboration. Several types of models were proposed to explain this structure in the literature. As pointed out by Burns and Swanson (arXiv:1603.04366), none of them provides a satisfactory description of the observation. We provide additional arguments using general properties of QCD, and conclude that the observation of the  $X(5568)$ , if confirmed, poses serious challenges to our understanding of nonperturbative QCD.

*Introduction.* Very recently, the D0 Collaboration reported the observation of a narrow peak in the  $B_s^0\pi^\pm$  invariant mass distribution based on data from  $p\bar{p}$  collisions at  $\sqrt{s} = 1.96$  TeV [1]. They fitted to the data using an  $S$ -wave (and a  $P$ -wave for studying systematic uncertainties) Breit–Wigner parametrization, and obtained a mass and width of

$$M_{X(5568)} = (5567.8 \pm 2.9_{-1.9}^{+0.9}) \text{ MeV}, \quad \Gamma_{X(5568)} = (21.9 \pm 6.4_{-2.5}^{+5.0}) \text{ MeV} \quad (1)$$

with a significance of  $5.1 \sigma$ . This observation has triggered a lot of theoretical calculations and speculations [1–18], most of which interpreted the signal as a resonance consisting of two quarks and two antiquarks, i.e.  $\bar{b}sq\bar{q}$  ( $q = u, d$ ), either of a compact tetraquark or meson-meson molecular structure. There is also an explanation using the so-called triangle singularity [8] by observing that the peak is located only about 13 MeV above the  $B_s^*\pi^\pm$  threshold, where the  $B_s^*\pi \rightarrow B_s\pi$  rescattering is required. A warning message was delivered in Ref. [17], where the difficulties of interpreting the signal as a tetraquark, a hadronic molecule or a threshold effect were discussed. In this short note, we want to sharpen the conclusions of Ref. [17] by using very general arguments from quantum chromodynamics (QCD) which include chiral symmetry and heavy quark symmetry. We will argue that if the  $X(5568)$  will be confirmed with the reported properties, then it would pose serious challenges to our understanding of nonperturbative QCD.

*Chiral symmetry.* The QCD Lagrangian has a  $\text{SU}(N_f)_L \times \text{SU}(N_f)_R$  symmetry, where  $N_f = 2$  or 3 is the number of light quark flavors, which is spontaneously broken to the vector subgroup  $\text{SU}(N_f)_V$ . Although the spontaneous breaking of chiral symmetry has not been proven theoretically, strictly speaking, there are strong evidences for it from both experiment and lattice QCD simulations. As a result, of this spontaneous symmetry breaking, there are  $N_f^2 - 1$  Goldstone

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bosons which are identified as the lightest pseudoscalar multiplet. This explains why the pion mass,  $M_\pi \simeq 138$  MeV, is much lighter than the mass of any other hadron. Chiral perturbation theory (CHPT) [19, 20] is the low-energy effective field theory for QCD based on chiral symmetry and its spontaneous breaking. At leading order, one has the Gell-Mann–Oakes–Renner relation  $M_\pi^2 = 2Bm_q \propto m_q$ , with  $m_q$  the light quark mass and  $B$  a positive constant. It is clear that the pion mass vanishes in the chiral limit  $m_q \rightarrow 0$ . In CHPT, one counts  $M_\pi = \mathcal{O}(p)$  with  $p \ll M_R$  being a small momentum scale where  $M_R$  denotes the mass of the lowest resonance, which can not be described in a perturbative expansion like CHPT. Any hadron other than the Goldstone bosons has a nonvanishing mass in the chiral limit, and this mass is of order  $\mathcal{O}(p^0)$ . This can be generalized to argue that introducing any additional quark-antiquark ( $q\bar{q}$ ) pair will add a mass of  $\delta m_{q\bar{q}} = \mathcal{O}(M_R) \gg M_\pi$ . The  $B_s$  is the ground state of  $\bar{b}s$  systems, and any excitation will increase the mass. We thus expect that a  $\bar{b}s\bar{q}q$  tetraquark to have a mass

$$M_{\bar{b}s\bar{q}q} \gtrsim M_{B_s} + M_R. \quad (2)$$

If we estimate  $M_R$  by the  $f_0(500)$  meson mass, which is the lowest meson resonance, then we get  $\sim 5.9$  GeV. It is much above the observed mass of the  $X(5568)$ , consistent with the expectation in Ref. [17] from the point of view of constituent quark model. The only possibility evading such a large mass is to generate a state from the interaction between bottom mesons and Goldstone bosons, more precisely, pions. If the interaction between matter field and pseudo-Goldstone boson is strong, then it is possible to generate a state close to the threshold. Since the reported mass is not far from the  $B_s\pi$  threshold, we discuss only the  $S$ -wave case. However, the low-energy pionic interaction is weak because of chiral symmetry. Furthermore, the leading order interactions in the chiral expansion in both of the  $B_s\pi$  and isovector  $B\bar{K}$  channels vanish, see, e.g., Ref. [21]. It is possible to generate a pole from coupled-channel effects. But then the pole should not be located only 60 MeV above the  $B_s\pi$  threshold. In fact, in the charmed sector, a pole can be generated by the isovector coupled-channel  $D_s\pi$ – $DK$  dynamics [21], but it is deep in the complex energy plane with a real part about 200 MeV higher than the  $D_s\pi$  threshold.

*Heavy quark symmetry.* In the heavy quark limit, for any hadron containing a single heavy quark, the heavy quark mass does not play a role in the dynamics (see, e.g., Ref. [22]). This leads to heavy quark flavor symmetry (HQFS). If the  $X(5568)$  is a hadron resonance, either being a compact tetraquark or of meson-meson type, it should have a charmed partner. The HQFS breaking effects are proportional to  $(1/m_c - 1/m_b)$  [22]. We therefore expect the charmed partner of the  $X(5568)$  to have a mass around

$$M_{X_c} = M_{X(5568)} - \bar{M}_{B_s} + \bar{M}_{D_s} + \mathcal{O}\left(\Lambda_{\text{QCD}}^2 \left(\frac{1}{m_c} - \frac{1}{m_b}\right)\right) \simeq (2.24 \pm 0.15) \text{ GeV}, \quad (3)$$

where  $\bar{M}_{B_s} = 5.403$  GeV and  $\bar{M}_{D_s} = 2.076$  GeV are the spin-averaged masses of the pseudoscalar and vector heavy-strange mesons. Within this mass range, the only candidate is the  $D_{s0}^*(2317)$  which was discovered by the BaBar Collaboration in the  $D_s\pi$  invariant mass distribution [23] and has a width of less than 3.8 MeV [24]. It is generally believed that the  $D_{s0}^*(2317)$  is an isospin scalar (isoscalar) meson, and its decay into the  $D_s$  and pion is due to isospin breaking effects, which has been proposed [25–27] to be used to discriminate the hadronic molecular interpretation [28–33] from other possibilities. The width of the  $X(5568)$  is about 20 MeV. The only allowed possible strong decay modes are the  $B_s\pi$  and  $B_s^*\pi$ , both of which are isovector. Therefore, were the  $X(5568)$  a hadronic resonance, its isospin should be 1, and hence the  $D_{s0}^*(2317)$  cannot be its charmed partner. One needs to answer the question why the charmed partner of the  $X(5568)$ , with a width ideal for observation, has not been observed in the same processes where the very narrow  $D_{s0}^*(2317)$  was observed.

*Could the  $X(5568)$  be due to  $B_s^*\pi$  threshold effects?* Liu and Li suggested to explain the peak as a triangle singularity effect observing that it is close to the  $B_s^*\pi$  threshold [8]. Their model involves the rescattering from  $B_s^*\pi$  to  $B_s\pi$ . This mechanism was questioned in Ref. [17] as such a process is too weak as it is in a  $P$ -wave and no flavor exchange is possible. Here we will show to what extent such a rescattering is suppressed. Around the  $X(5568)$  peak, the pion

momenta in both  $B_s\pi$  and  $B_s^*\pi$  are low. Thus, we can describe such a process by an effective chiral Lagrangian respecting heavy quark symmetry. We denote the  $B_s$  and  $B_s^*$  spin multiplet by a superfield  $H_s = \vec{B}_s^* \cdot \vec{\sigma} + B_s$  [34], where  $\vec{\sigma}$  are Pauli matrices, which transforms under parity ( $\mathcal{P}$ ) and heavy quark spin ( $\mathcal{S}$ ) transformations as

$$H_s \xrightarrow{\mathcal{P}} -H_s, \quad H_s \xrightarrow{\mathcal{S}} SH_s, \quad (4)$$

where  $S$  is the rotation matrix acting on the heavy quark spin, and does not commute with the Pauli matrices. The lowest order operators, preserving heavy quark spin symmetry, in the chiral expansion that have a nonvanishing contribution to  $B_s^*\pi^\pm \rightarrow B_s\pi^\pm$  are

$$i\epsilon_{ijk} \langle H_s^\dagger \partial^i H_s \sigma^j \rangle \partial^k (\chi_+)_{aa}, \quad i\epsilon_{ijk} \langle H_s^\dagger H_s \sigma^i \rangle ([u^j, u^k] \chi_+)_{aa}, \quad (5)$$

where  $\langle \rangle$  denotes the trace in the spinor space and  $a$  is the light flavor index. Here  $\chi_+$  and  $u^i$  are the usual building blocks of chiral Lagrangians. They contain an even number and an odd number of pion fields, respectively, and read  $\chi_+ = 2\chi - \{\pi, \{\pi, \chi\}\}/(4F^2) + \dots$  and  $u^i = -\partial^i \pi/F + \dots$ , where  $\chi = 2B \cdot \text{diag}(m_u, m_d)$ ,  $F$  is the pion decay constant in the chiral limit, and  $\pi$  is the usual  $2 \times 2$  matrix for the pion isospin triplet. These operators are doubly suppressed: (1) the lowest order possible operators in the chiral expansion, as given above, are of  $\mathcal{O}(p^4)$ , the next-to-next-to-next-to-leading order, in the chiral expansion for the interaction between Goldstone bosons and matter fields, and thus highly suppressed; (2) the bottom-strange mesons and pions do not have a common flavor, and the interaction is thus OZI suppressed or  $1/N_c^2$  suppressed (a relative  $1/N_c$  suppression in comparison with those scattering processes with a common quark flavor), with  $N_c$  the number of colors. These strong suppressions make less likely explaining the observed peak by invoking  $B_s^*\pi \rightarrow B_s\pi$  rescattering.

*Summary.* To summarize, our arguments based on chiral symmetry and heavy quark symmetry support the analysis in Ref. [17] that it is hard to explain the properties of the  $X(5568)$  using either tetraquark, hadronic molecule, or threshold-effect models. If the observation of the  $X(5568)$  is confirmed, it would have an important impact on the understanding of nonperturbative QCD. We thus suggest to search for it in other processes such as the dipion decays of excited bottom-strange mesons, e.g.,  $B_{s2}^*(5840) \rightarrow B_s\pi\pi$ , and search for its charmed partner using the huge data sets of  $B$  factories. In fact, the LHCb Collaboration did not see a signal corresponding to the  $X(5568)$  based on their  $pp$  collision data [35].

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